Factors Affecting HCCI Combustion Phasing for Fuels with Single- and Dual-Stage Chemistry

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Introduction

- HCCI engines can provide diesel-like efficiencies and ultra-low NO_X and PM emissions – However there are several technical barriers.

- Control of combustion phasing with changes in fueling rate is particularly important.
  - Various control techniques are available: intake heating, VCR, VVT.
  - Ultimately adjust the compressed-gas temperature (T_{CG}) at “ignition.”

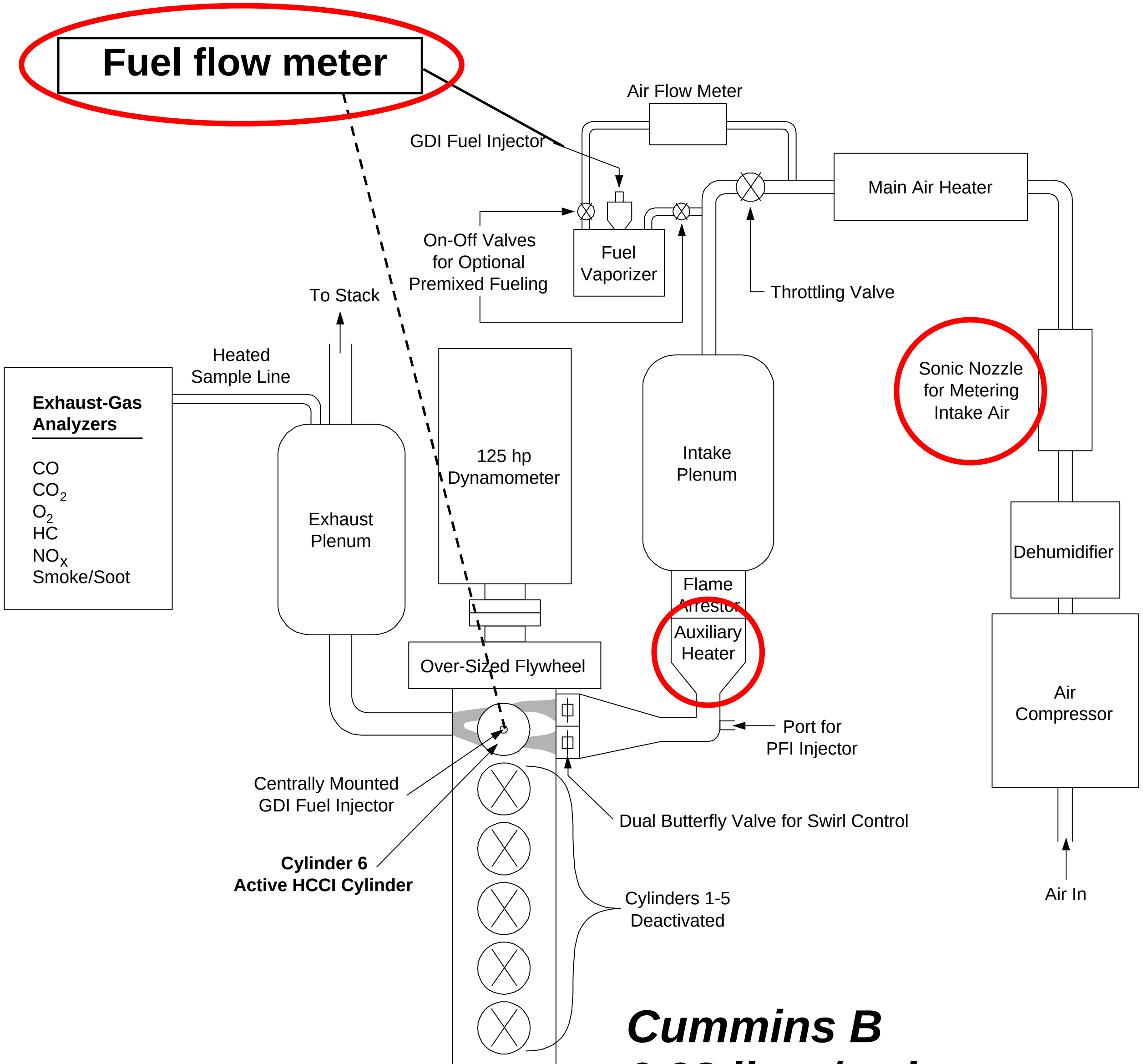
- Often considered that combustion phasing can be affected by F/A mixture $\Rightarrow$ Ignition is faster with richer mixtures created by higher fueling rates or charge-mixture inhomogeneities.

- However, as the fuel load is varied, several factors are affected, each of which can affect combustion phasing.
  - Most factors directly or indirectly cause changes in the T_{CG}.
  - Additionally, these factors can sometimes mask changes – or lack of changes – due directly to F/A-mixture effects.

Objectives

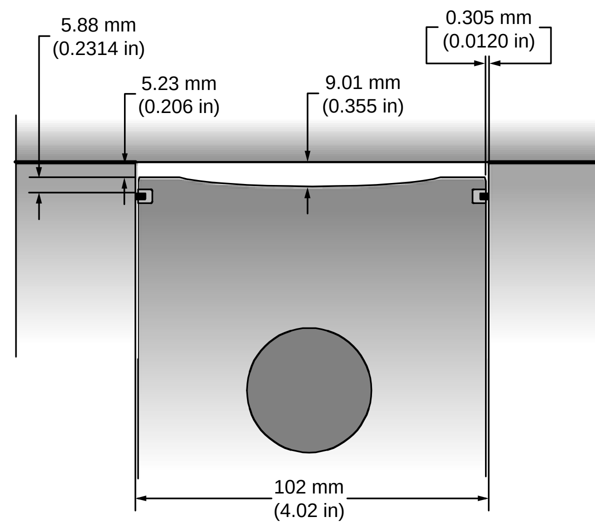
- Identify the factors that cause changes in combustion phasing with changes in fueling rate (fuel-air equivalence ratio, ϕ).
- Systematically remove the changes due to each factor.
  - Understand the relative magnitude of these factors.
- Isolate the effect of changes in fuel chemistry with equivalence ratio to understand the importance of this factor.
  - Compare behavior of various fuel-types: iso-octane, gasoline, & PRF80.
- Investigate the potential of fuel stratification for controlling combustion phasing.

HCCI Engine and Subsystems



Cummins B
0.98 liter / cyl.

Piston design:



<u>Base Condition</u>

CR: 17.6

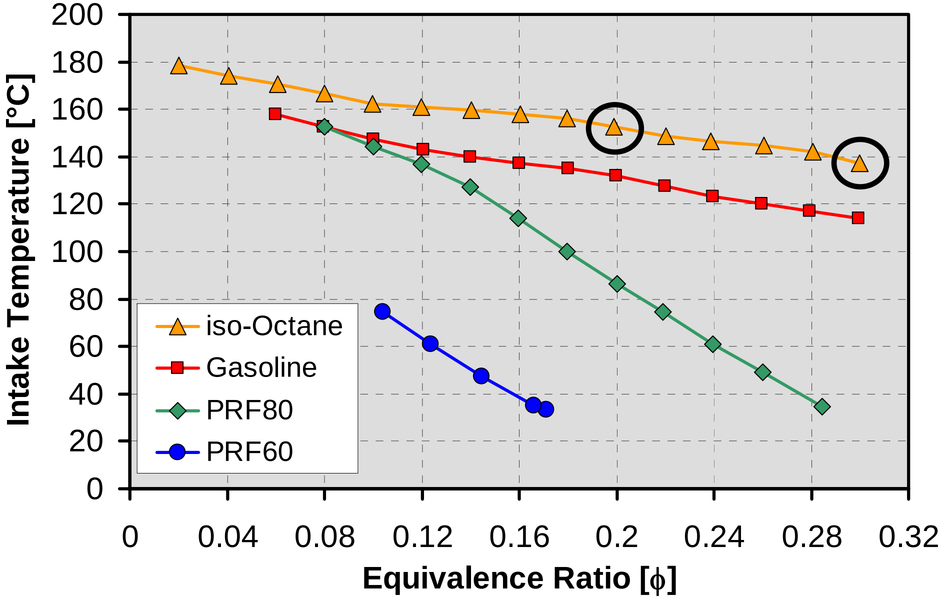
Swirl ratio: 0.9

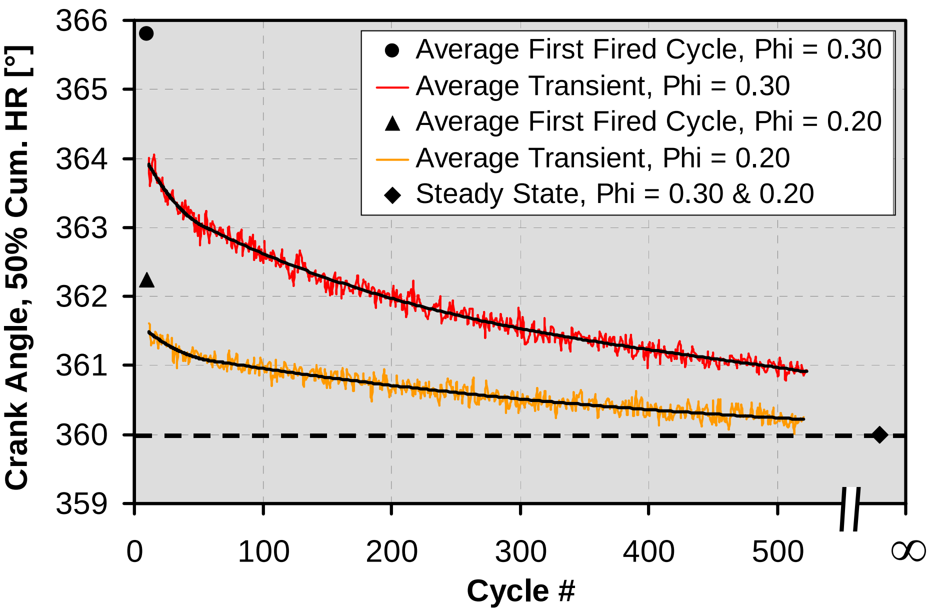
Speed: 1200 rpm

P_{in} : 100 kPa

<u>Fueling</u>: Premixed
GDI

Observed Changes with Variation in Fueling





- As fueling (ϕ) is varied, T_{CG} must be adjusted to maintain combustion phasing.
  - 50%-burn phasing at TDC (indication of performance).
  - Adjust T_{CG} by varying Intake temperature (T_{in}).
- All fuels show a trend of a lower required T_{in} with increased ϕ.
  - Do richer mixtures autoignite more easily for all fuels?
  - What role do other factors play?
- For example, wall heating and residuals will change with ϕ.
  - Figure shows fuel-on transients for ϕ = 0.2 and 0.3, iso-octane (avg. of 10 events).

SAE 2004-01-0557

Factors Causing Changes in T_{in} with Fueling

1. Combustion duration increases at lower ϕ. This requires that the start of combustion occur earlier to maintain 50% burn at TDC.

2. Wall temperatures increase with increased ϕ, causing higher T_{CG} for a given T_{in}.

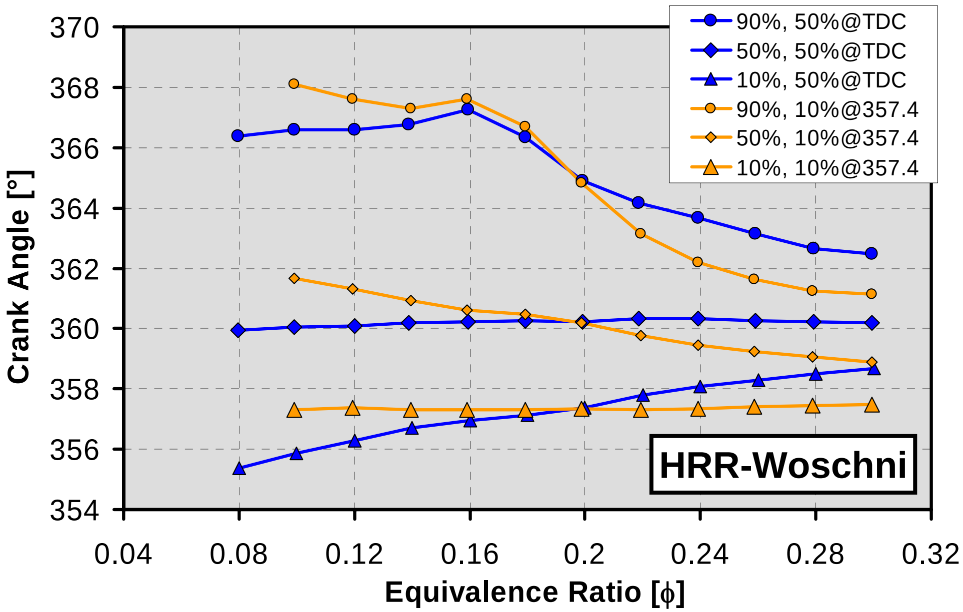
3. Temperature of residuals increases with ϕ, reducing required T_{in}.

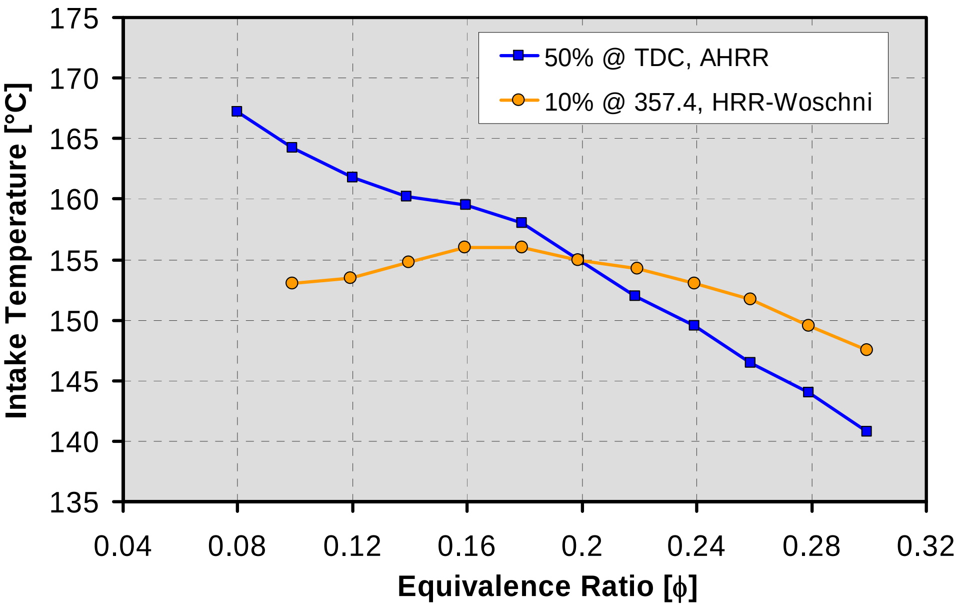
4. Heating/cooling during induction changes with ϕ as the ΔT between T_{in} and T_{wall} varies, amount of fuel vaporization, & "dynamic heating."

5. Fuel-chemistry effects.
   – Differences in ϕ can affect the chemical-kinetic rates of autoignition.
   – Thermodynamic properties of mixture – particularly specific heat ($\gamma=c_p/c_v$).

- Systematically remove factors 1-4 leaving only fuel-chemistry effects.
  – Evaluate differences in fuel chemistry: <u>iso-octane</u>, gasoline, & PRF80.

1. Changes in Combustion Duration

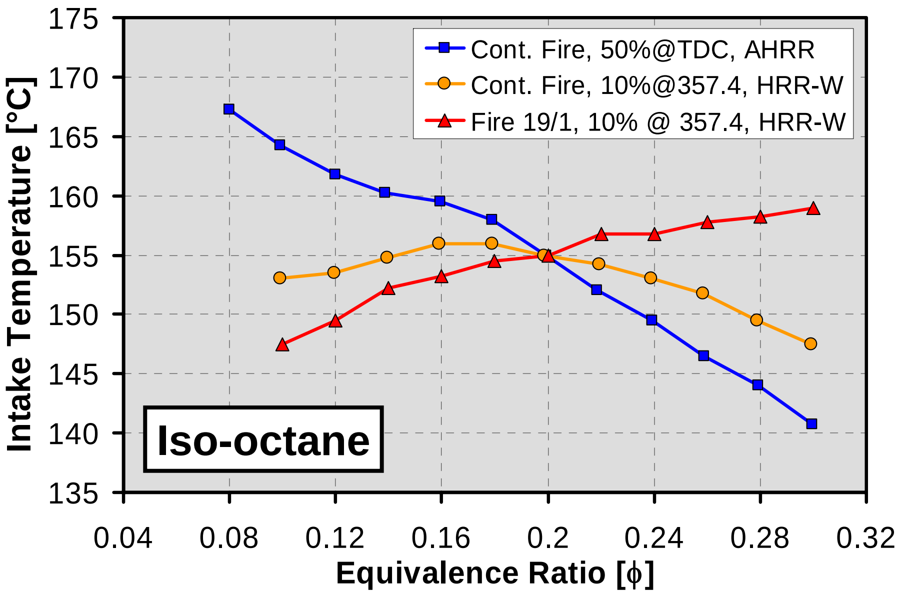


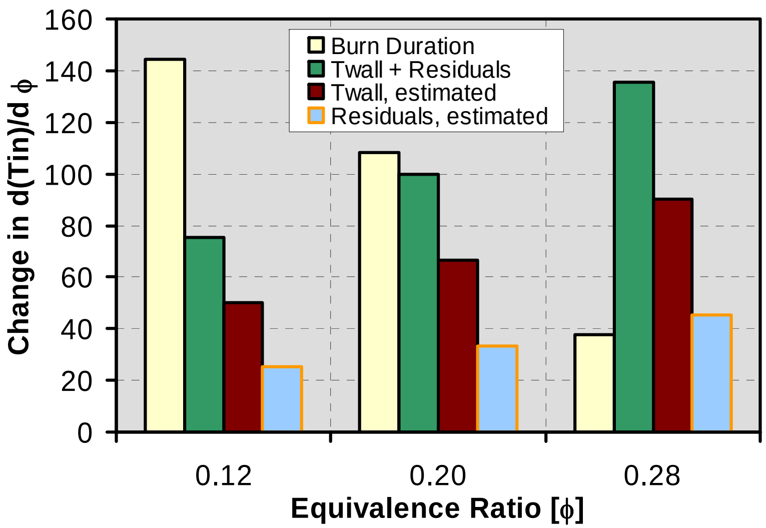


<u>Base Fuel: Iso-Octane</u>

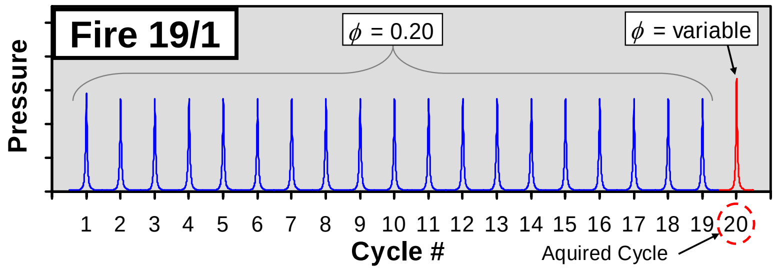
- Burn duration increases as ϕ reduced.
  - Phasing remains very stable – Std. Dev < 0.3°CA for 10 & 50% burn over range of interest.
  - $0.1<\phi<0.3$ (idle to moderate load).
- Fuel-chemistry effects should correlate with ignition point.
- Select 10% burn as “ignition” pt.
  - Use Woschni correlation to account for heat transfer.
- Retake data with const. 10% burn at 357.4°CA, match ϕ=0.2.
  - Change in T_{in} with ϕ is greatly reduced, from 24°C to 8.5°C.

2 & 3. Remove Changes in T_{wall} and Residuals





- Remove changes in T_{wall} & residuals using alternate-firing technique.
  - Hold 10% burn phasing at 357.4°.



- Reverses trend – higher T_{in} with higher ϕ.
- Change in slope between the curves gives relative magnitude of factors.
  - $\phi < 0.2$, burn duration dominates. comb. eff. low: long burn, low heating.
  - $\phi > 0.2$, opposite is true.
- Separate T_{wall} & residual effects estimated from transient data and fire18/2 data.

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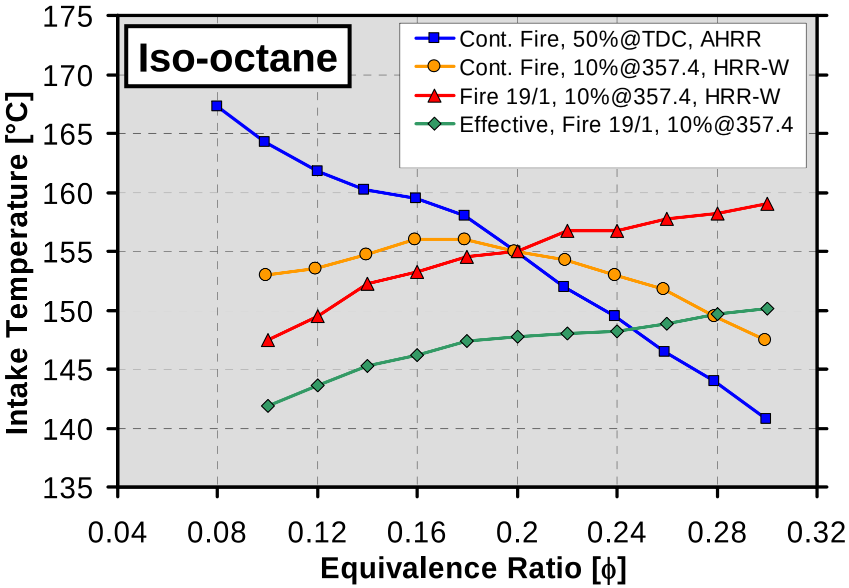
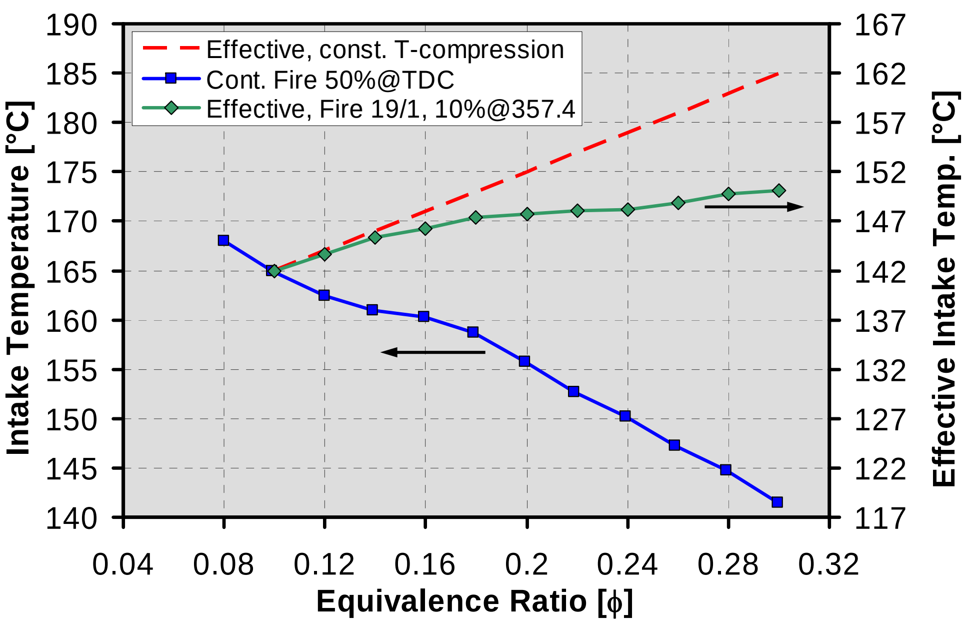
4. Heating/Cooling During Induction

- $T_{in} \neq T_{BDC}$ due to heating/cooling during induction.
- Developed technique to estimate $T_{BDC} \Rightarrow$ Details in SAE 2004-01-1900.
- Compute changes in T_{BDC} from measured changes in mass flow relative to a base condition.
- Ideal gas law gives: $$T_{in,effective} = T_{in,effective,base} \cdot \frac{m_{air,base}}{m_{air+fuel}} \cdot \frac{M_{air+fuel}}{M_{air}} \cdot \cancelto{1}{\frac{P_{in}}{P_{in,base}}}$$
- Base condition: motored $T_{in} = T_{coolant} = 100°C$, minimizes heat transfer.
  - Dynamic heating $\Rightarrow T_{BDC,\ base} = 110°C$ (from WAVE code, Ricardo).
- Estimate $T_{residuals} \approx$ average of $T_{exhaust}$ and $T_{blowdown}$.
- Combine to get: $$T_{bdc} = \frac{T_{in,effective} \cdot m_{air+fuel} + T_{residuals} \cdot m_{residuals}}{m_{air+fuel} + m_{residuals}}$$
- A straightforward procedure. Technique is very sensitive.

4 & 5. Use T_{BDC} to Isolate Effects of Fuel Chemistry

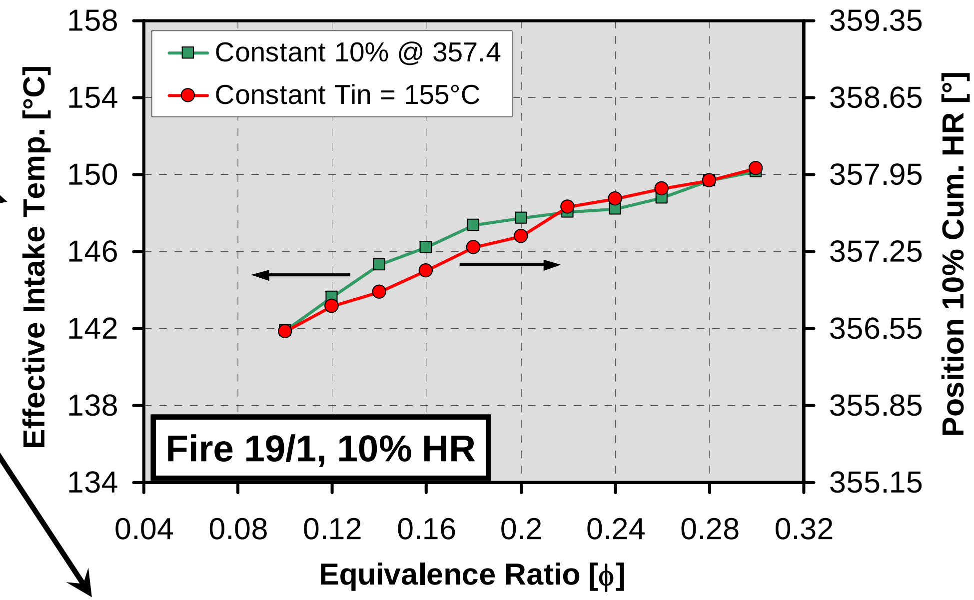


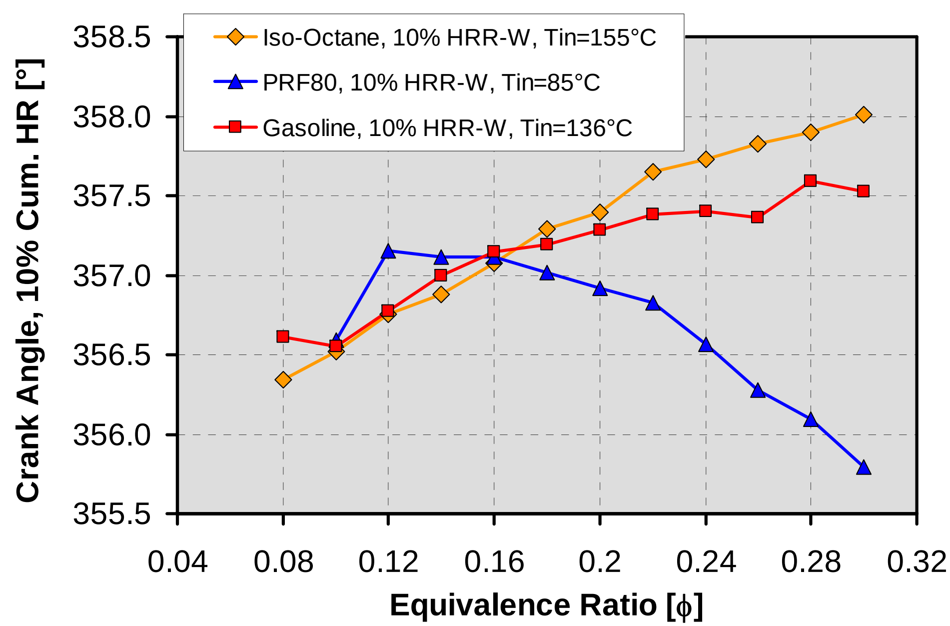


- For fire19/1, residuals are constant; use effective T_{in} rather than T_{BDC}.
- Effective T_{in} curve shows only changes due to fuel-chemistry.
  - Autoignition kinetics & $\gamma = c_p/c_v$.
- Does a higher ϕ enhance autoignition for iso-octane?
  - Higher $\phi \Rightarrow$ smaller $\gamma \Rightarrow$ higher T_{in} required for same T_{CG}.
- Lesser slope of Effective T_{in} curve indicates an enhancement with ϕ.
  - Effect fairly small for iso-octane.
    - > Much less than sum of other four factors.
  - Single-stage ignition fuel.

5. Fuel-Chemistry Effects – Various Fuels

- Alternatively, hold T_{in} constant and observe changes in phasing.
  - Trends similar to effective T_{in}.
- The 10%-phasing curves show isolated fuel-chemistry effects.
- Iso-octane: enhancement of ignition kinetics < effect of γ.
- Gasoline: a little more enhancement of ignition kinetics with increased ϕ than iso-octane.
- PRF80: autoignition kinetics greatly enhanced with ϕ.
  - Correlates with increasing cool-flame chemistry with ϕ (infers diesel fuel).
  - At low ϕ cool-flame activity is minimal, and trend is similar to iso-octane.

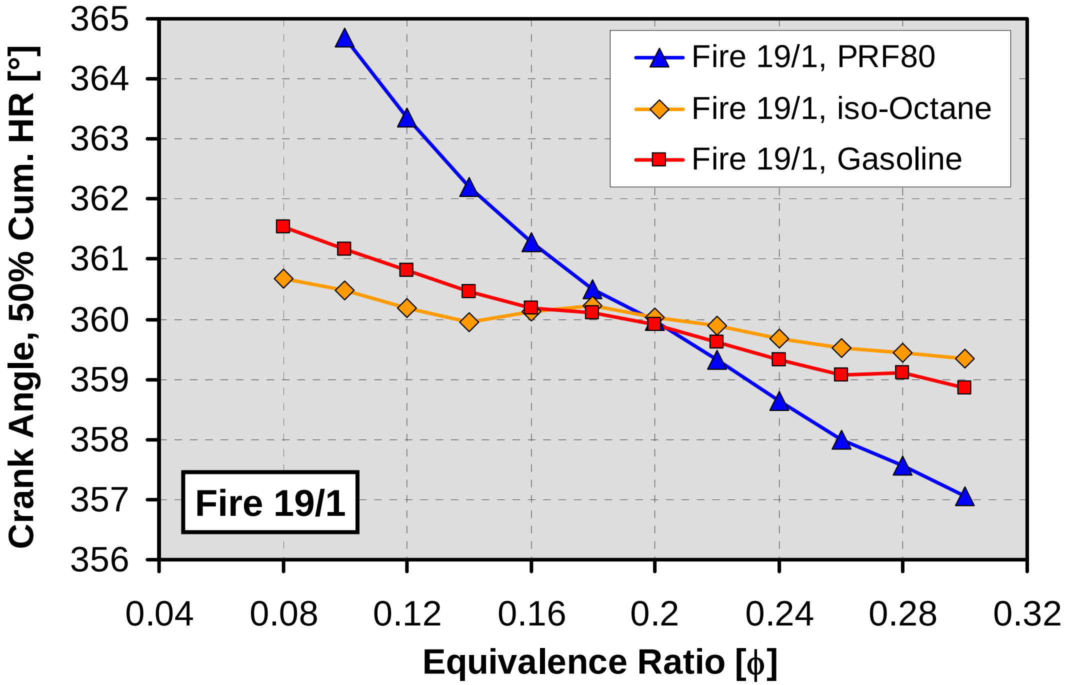




50% Burn Phasing for Constant T_{in} and T_{wall}

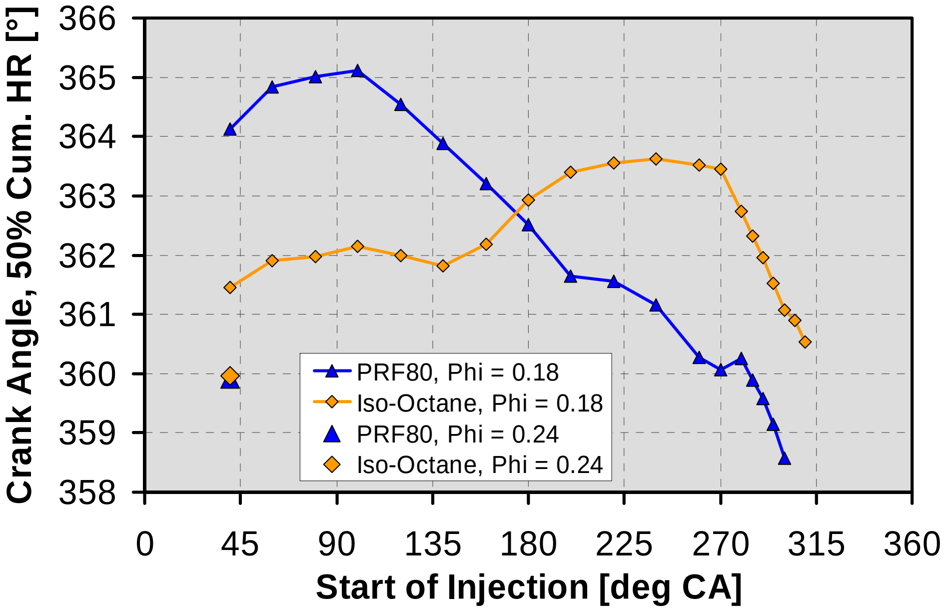
- 50% burn is a better indicator of engine performance.

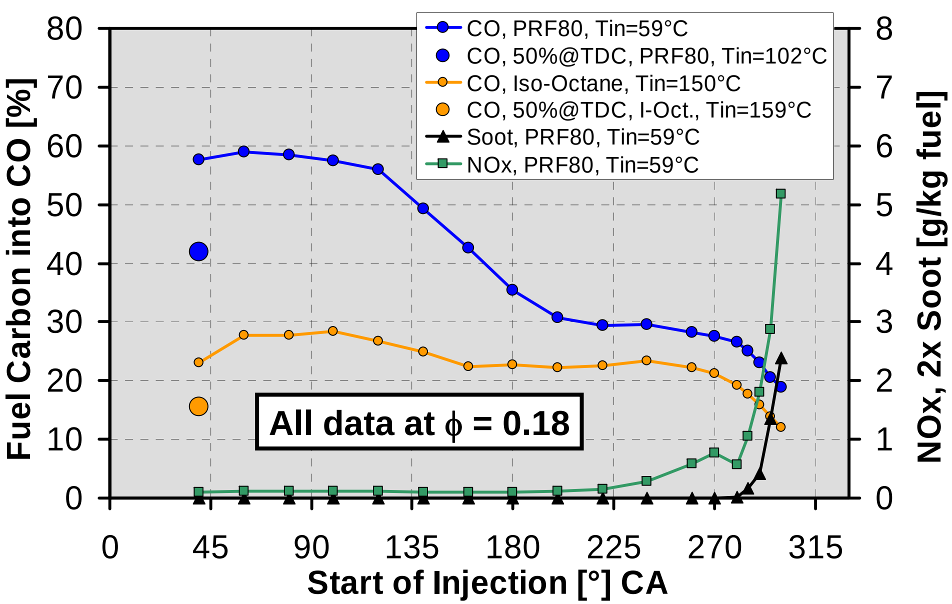
- Fire 19/1 data simulates behavior during a rapid load change before T_{in} and T_{wall} can respond.
  - Iso-octane & gasoline: small variation, little compensation required. $\Rightarrow$ single-stage ignition
  - PRF80: large variation, significant compensation required. $\Rightarrow$ dual-stage ignition (cool-flame chem.)



- Data can also be interpreted as indicating the potential for changing combustion phasing with mixture stratification (T_{wall} & residuals constant).
  - PRF80: mixture stratification has a strong potential to control phasing.
  - Iso-octane and gasoline: stratification offers little benefit for phasing control.

Stratification Advances Combustion for PRF-80





- PRF80: simulate load change from $\phi = 0.24 \Rightarrow 0.18$.
  - $\phi = 0.24$, T_{in} = 59°C for 50% burn at TDC.
  - $\phi = 0.18$, T_{in} = 102°C for 50% burn at TDC.
- Stratification can rapidly adjust phasing for PRF80.
  - Injection at 270°CA, in phase.
  - Also, improves combustion eff., as shown in SAE 2003-01-0752.
- Iso-octane: stratification does not advance phasing.
  - Weak enhancement of autoignition kinetics with ϕ.
  - Does not overcome charge cooling due to vaporization.

SAE 2004-01-0557

Summary and Conclusions

- In addition to fuel-chemistry, several factors affect the change in intake-temperature required to maintain constant 50%-burn phasing when the fueling rate is varied.

- The relative magnitude of these factors depends on the load range.
  - At low loads, ($\phi < 0.2$), changes in burn duration have the largest effect.
  - For higher loads ($\phi > 0.25$), changes in T_{wall} are dominant.

- The effect of residuals is relatively small in this engine.
  - They could be the dominant factor in a high-residual engine.

- The effect of F/A mixture (ϕ) on ig. timing depends strongly on fuel type.
  - Single-stage ignition fuels: iso-octane & gasoline $\Rightarrow$ effect is small.
  - Dual-stage ignition fuels: PRF80 $\Rightarrow$ effect is substantial due to cool-flame chemistry. (Similar effect expected for diesel fuel.)

- Mixture stratification can significantly and rapidly advance combustion phasing for PRF80 (or by inference diesel fuel), but not for iso-octane.